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Improving the environmental performance of bio-waste management with life cycle thinking (LCT) and life cycle assessment (LCA)

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Abstract
Background Globally, many countries worldwide aim at increasing the environmental sustainability of waste management activities. Special attention is devoted to bio-waste, as its improper handling may have severe environmental consequences. In particular, most waste management strategies should encourage diverting bio-waste away from landfills to reduce emissions of greenhouse gases and leachate.
Legislative context The European Waste Framework Directive (WFD 2008/98/EC) defines bio-waste as "biodegradable garden and park waste, food and kitchen waste from households, restaurants, caterers and retail premises and comparable waste from food processing plants". Bio-waste should not be confused with the wider term "biodegradable waste", which covers also other biodegradable materials such as wood, paper and cardboard. In Europe, landfilling of untreated bio-waste is being progressively reduced to meet the requirements set by the Landfill Directive (1999/31/EC). Other options for bio-waste management are then prioritised (e.g. biological treatment), in line with the so-called waste hierarchy, the legally binding priority order for waste management established by the Waste Framework Directive (2008/98/EC).
Method and outcome However, following the waste hierarchy may not always lead to the identification of the most environmentally sound option, and new approaches are thus needed for a more differentiated and science-based support to decision-making for bio-waste management. For this purpose, the Institute for Environment and Sustainability of the Joint Research Centre has developed guidelines that provide environmentally sound support to decision-making and policy-making for bio-waste management using life cycle thinking and life cycle assessment. The methodological approach developed in these guidelines is presented and contextualised in this paper.

Keywords Bio-waste management · Life cycle assessment · Life cycle thinking · Waste hierarchy

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1 Introduction

1.1 Background and purposes

Large quantities of bio-waste are produced yearly in many countries around the globe: in Europe, more than 1/3 of the bio-waste generated is still landfilled. Improper management of bio-waste has shown to have adverse environmental effects, especially in terms of greenhouse gas emissions.

In order to provide a more informed and science-based support to policy-making, the EU Joint Research Centre (JRC) has recently developed guidelines on how to use life cycle thinking (LCT) and life cycle assessment (LCA) for an environmentally sound decision support for bio-waste management. These provide practical guidance on how to recognise key technical and environmental parameters and identify the environmentally preferable options for bio-waste management (EC 2010). This paper summarises the main guidance aspects and highlights the key findings.

1.2 European bio-waste management: an overview

Approximately 120 to140 million tonnes of bio-waste are produced every year in the EU (COM 235 2010), which

corresponds to about 300 kg per average EU citizen per year. The Waste Framework Directive (WFD 2008/98/EC) defines bio-waste as "biodegradable garden and park waste, food and kitchen waste from households, restaurants, caterers and retail premises and comparable waste from food processing plants". Bio-waste does not include forestry or agricultural residue and thus should not be confused with the wider term "biodegradable waste", which covers also other biodegradable materials such as wood, paper, cardboard, sewage sludge, natural textiles, etc. Biodegradable waste is defined in Article 2 (m) of the Landfill Directive (LD) (Directive 1999/31/EC) as "any waste that is capable of undergoing anaerobic or aerobic decomposition, such as food and garden waste, and paper and paperboard."

Improper management of biodegradable waste has widely shown to contribute to a variety of environmental issues, such as climate change, ecotoxicity and human toxicity. In particular, conventional landfilling (i.e. without gas energy recovery and leachate treatment) of untreated bio-waste and, in general, of biodegradable waste is seen as the least desirable management option for bio-waste. In Europe, measures to decrease landfilling of biodegradable waste have been enforced since the late 1990s. The LD, in fact, requires member states by 2016 (or, for some member states by 2020) to reduce landfilling of biodegradable municipal waste to 35 % of the total biodegradable municipal waste produced in 1995.

However, the LD does not prescribe specific treatment options for the diverted waste. In practice, member states may be inclined to choose the seemingly easiest and cheapest option, disregarding actual environmental benefits and costs including burdens which may be created elsewhere.

The European Commission is setting out priority actions to optimise bio-waste management in Europe, which are expected to bring environmental benefits as well as financial savings and social advantages. The Waste Framework Directive (2008/98/EC) requires member states to develop waste management policies that protect the environment and human health while ensuring the sustainable use of natural resources. In particular, the WFD:

- Establishes a legally binding priority order for waste management, the so-called waste hierarchy: "the following waste hierarchy shall apply as a priority order in waste prevention and management legislation and policy: (a) prevention; (b) preparing for re-use; (c) recycling; (d) other recovery, e.g. energy recovery; and (e) disposal" (Art. 4(1));
- Promotes the use of LCT to complement the waste hierarchy and help select the best environmental options for waste management: "When applying the waste hierarchy […], Member States shall take measures to encourage the options that deliver the best overall environmental outcome. This may require specific waste streams departing from the hierarchy where this is justified by life cycle thinking on the overall impacts of the generation and management of such waste" (Art. 4(2));
- Encourages member states to collect separately and recycle bio-waste and allows including it when calculating the binding recycling target for municipal waste (Art. 22);
- Enables the setting of EU minimum requirements for bio-waste management and criteria for the quality of compost from bio-waste, including requirements on the origin of the waste and treatment processes. Such criteria have been called for to enhance user confidence and strengthen the market in support of a material efficient economy (Art. 22).

The Commission Communication on future steps in bio-waste management in the European Union (COM 235 2010) provides the steps that are considered necessary for improving the overall environmental performance of current bio-waste management systems and stresses that bio-waste management should follow the "waste hierarchy", as defined in the WFD.

1.3 Next steps towards a more environmentally sound management of bio-waste

The Institute for Environment and Sustainability (IES) of JRC of the European Commission (EC) has developed guidelines ("Supporting Environmentally Sound Decisions for Bio-Waste Management—A practical guide to Life Cycle Thinking (LCT) and Life Cycle Assessment (LCA)") to further support environmentally sound decision-making in bio-waste management. This is part of broader set of technical reports (JRC waste technical guidelines, 2011) developed by the JRC, which also include:

- Guidelines for the overall municipal solid waste: "Supporting Environmentally Sound Decisions for Waste Management—A technical guide to Life Cycle Thinking (LCT) and Life Cycle Assessment (LCA) for waste experts and LCA practitioners";
- Guidelines for construction and demolition (C&D) waste: "Supporting Environmentally Sound Decision for C&D waste Management—A practical guide to Life Cycle Thinking (LCT) and Life Cycle Assessment (LCA)".

These guidelines build on the International Organization for Standardization (ISO) 14040 and 14044 standards for LCA and the International Reference Life Cycle Data System (ILCD) Handbook.

This paper is aimed at giving insights on the methodological approach presented in the above-mentioned guidelines for bio-waste management. It is mainly aimed at waste policy

makers, waste managers and civil servants supporting public decision makers.

2 Supporting environmentally sound management of bio-waste taking a life cycle perspective

2.1 Methodological approach

A decision tree is provided (Fig. 1) and illustrates the suggested approach to identify the preferable environmental option for bio-waste management taking a life cycle perspective. As a starting point, the waste management context in which decisions need to be taken should be identified. For instance, one should try to identify the management options available and their known or foreseeable environmental implications. The next sections move along the main steps illustrated in the decision tree.

2.2 Applying the waste hierarchy to bio-waste management

As a second step towards identifying the bio-waste management option that delivers the best environmental performance, the waste hierarchy should be considered. This requires "converting" the waste hierarchy as defined in the WFD into its equivalent form for the waste stream being considered, here bio-waste. We suggest the following interpretation of the waste hierarchy applied to bio-waste (Fig. 2):

- Prevention: generation of bio-waste can be avoided in a number or ways, such as smart food consumption/ wastage (e.g. buying only what is needed) and smart gardening (e.g. choosing low-yield plant species, grass mulching).
- Anaerobic digestion (with energy recovery) with composting of the liquid digestate and use on land as fertiliser of the composted output. Alternatively, the liquid digestate can be directly used on land, though this offers fewer environmental benefits than compost directly generated from bio-waste. In any case, a condition for high-quality output material is that separate collection of the bio-waste stream is implemented, so that the risk of contamination is minimised.
- Composting with use on land of compost for soil improvement; again, separate collection of the bio-waste stream is necessary for producing high-quality compost.
- Incineration with energy recovery.
- Mechanical–biological treatment (MBT) of bio-waste followed by conventional landfilling (here intended without energy recovery, but implementing technical measures to prevent emissions to the environment, such as leachate collection and treatment, gas collection and treatment in flares, top soil cover, etc.).

It should be mentioned that in the last two to three decades new, highly engineered landfilling technologies have been developed—which are at present fully established

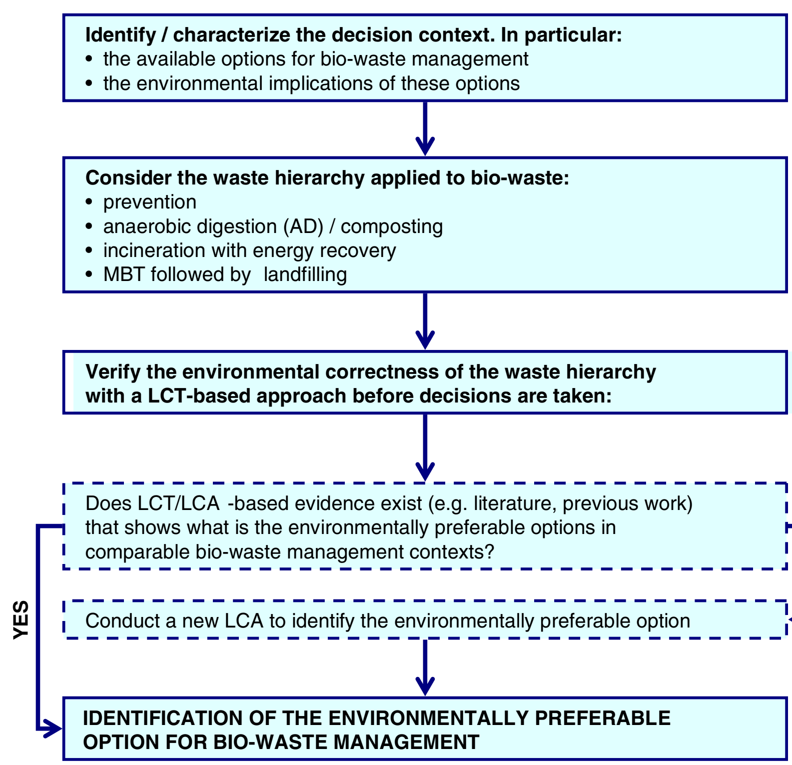

Fig. 1 Methodological approach to identify the environmentally preferable option for bio-waste management

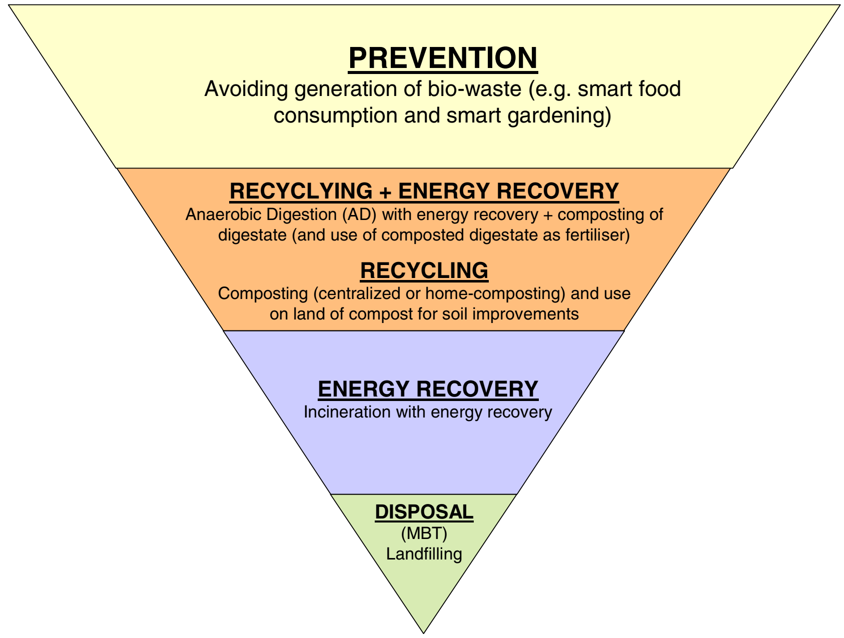

Fig. 2 Waste management hierarchy applied to bio-waste

in various industrialised countries—such as, for instance, bio-reactor landfills. These implement measures to prevent uncontrolled emissions of leachate to the subsurface, as well as measures to optimise waste degradation, collect and utilise the generated gas for energy generation. As a result, environmental impacts are substantially decreased compared to old fashioned, poorly engineered landfills. Also, LCT-based evidence exists showing that net environmental benefits may be achieved when landfill gas is extensively used for energy generation, provided that all measures to prevent emissions of leachate and gas are enforced (Manfredi and Christensen 2009).

However, in line with the LD (1999/31/EC), landfilling of biodegradable waste is on the decline in Europe and, as a consequence, the actual potential for gas generation is being progressively reduced. This makes it less and less attractive (technically, economically and environmentally) to use the little gas generated for energy generation purposes. For this reason, in line with the waste hierarchy as defined in the WFD, landfilling with energy recovery is not included in the waste hierarchy applied to bio-waste under the level "energy recovery" (see Fig. 2).

2.3 Verifying the correctness of the waste hierarchy with an LCT-based approach

Very often, following the waste hierarchy leads to the environmentally best solution and the decision-making process is easy, fast and cost effective. However, in specific circumstances, there may be a need to deviate from the waste hierarchy in order to select the best solution for the environment. Also, in some cases, a number of alternatives exist at a given level of the waste hierarchy (e.g. centralised composting or home composting), which may not be equivalent from an environmental perspective. That is why the WFD, while confirming the status of the hierarchy as the primary reference for waste management, wisely opens to potential deviations if these are justified by LCT on the overall environmental impact.

Many LCT-based approaches exist that can be used to support decision-making in waste management, including life cycle costing, cost benefit analysis, material flow analysis and LCA. Amongst these, LCA is perhaps the most extensively used when environmental protection is the key focus. LCA is a comprehensive, quantitative approach that assesses the emissions, resources consumed and pressures on health and the environment. Due to its comprehensive and quantitative nature, LCA allows for fair comparison of the environmental performance of different waste management options. LCA can thus be used to complement the waste hierarchy and unambiguously identify the best performing option for the environment.

However, testing the environmental appropriateness of the waste hierarchy by conducting a new LCA may not always be necessary. In fact, there may be instances in which LCT/LCA-based evidence from previous work may show that the issue can be approached, if not solved, in a similar manner. Existing available studies on comparable decision-making contexts should therefore be scrutinised. To ensure quality and consistency, these studies should preferably be ISO compliant and should have undergone a critical review. A critical review assesses whether an LCA or related data have met predefined requirements. This can help avoid errors and ensure that all options or method requirements have been appropriately taken into consideration.

When appropriate LCT/LCA-based evidence from existing studies is not available or do not meet the desired quality, then a new LCA needs to be conducted to support decision-making and, ultimately, identify the best overall environmental option. Section 2.5 expands on this.

2.4 Practical step-by-step guidance

Figure 3 provides practical guidance on how to support sound environmental decisions for bio-waste management and will help to ask the relevant questions in the right context before decisions are taken prematurely. However, please note that any provided figures for making "yes–no" decisions should be taken with the necessary caution. These figures may not cover all relevant cases but can be taken as an indication. The rational is to follow the priority order of waste management set by the waste hierarchy and to systematically check:

- Whether a certain treatment/management option is available or can be made available, e.g. whether an anaerobic digestion (AD) plant exist in the waste management context under study, whether it would provide sufficient capacity or, if not, whether increasing its capacity or building a new facility is feasible;
- Whether LCT/LCA-based evidence from previous work exist (for comparable contexts) that help identify the best option. If this is not the case, the best overall environmental option should be established by conducting a new LCA.

AD is assumed to include either composting of the liquid digestate followed by use on land of the final output as fertiliser (preferred option) or direct use of the liquid digestate on land. Also, AD is always assumed to include energy recovery. Composting is intended as always including use on land of compost for soil improvement. Incineration is intended with the highest possible energy recovery efficiency. As explained in Section 2.2, landfilling is here intended without energy recovery but still implementing measures to prevent emissions of gas and leachate to the environment.

The practical guidance reads as follows:

- Prioritise bio-waste prevention when it is possible and beneficial for the environment, e.g. when it does not negatively affect other stages in the life cycle. For example, bio-waste prevention may lead to environmental benefits when bio-waste is used as sustainable bio-fuel. In many cases, however, establishing whether or not bio-waste prevention leads to net environmental benefits is not obvious. For instance, prevention of green waste from park and gardens may, or may not, be environmentally beneficial depending on what management route the green waste would follow if they were not prevented (e.g. anaerobic digestion or landfilling). In all of these cases, LCT/LCA should be used (i.e. existing evidence from previous work or conducting a new LCA) to establish whether performing bio-waste prevention is environmentally advantageous.
- Check whether the waste stream is too contaminated to allow any produced compost/digestate to be used on

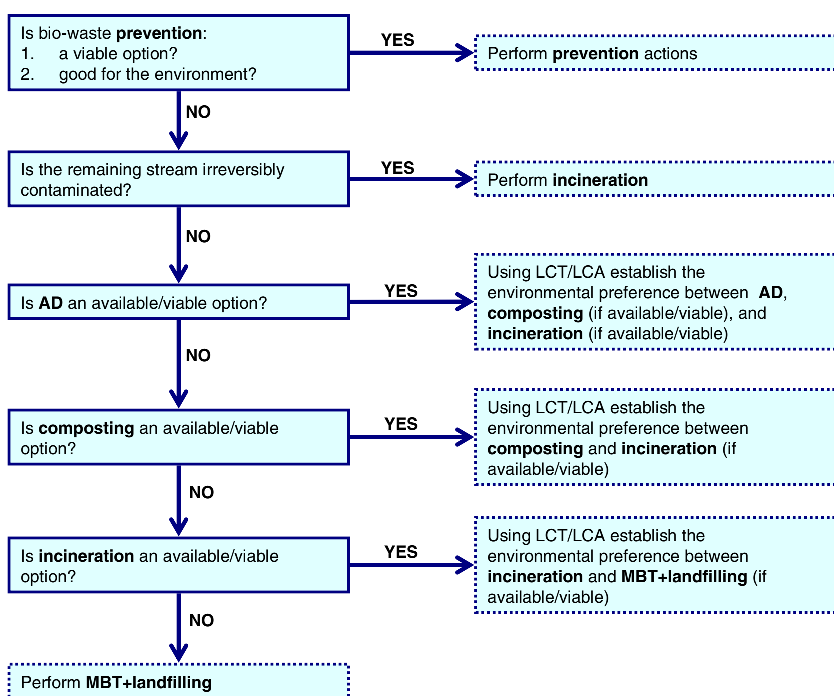

Fig. 3 Practical guidance to support sound environmental decisions for bio-waste management

land. In this case, only incineration with energy recovery can be envisaged.

- For the streams that could not be prevented and are not contaminated, AD is favoured, as long as it is an available/viable option. The rationale is to combine both producing valuable digestate (which preferably should be composted) to be used as fertiliser and efficient energy recovery. However, if composting and incineration are also available/viable options, then LCT/LCA should be used (i.e. evidence from previous work or conducting a new LCA) to identify the preferable environmental option among AD, composting and incineration.
- If anaerobic digestion is not an available/viable option, compositing is envisaged. The compost benefits are the same (if not higher) as for anaerobic digestion, except that there is no energy recovery. Again, if incineration with energy recovery is also an available/viable option, then LCT/LCA should be used (i.e. evidence from previous work or conducting a new LCA) to identify the preferable environmental option between composting and incineration.
- If neither AD nor composting are available/viable options, then incineration should be favoured (if available/viable) as long as LCT/LCA-based evidence exists or can be produced that incineration performs better (from an environmentally view point) than MBT followed by landfilling.
- When incineration with energy recovery also is not an available/viable option, no (significant) benefit can be drawn from bio-waste treatment and the bio-waste can be treated together with other waste streams (no source separated collection needed). Landfilling is therefore the remaining option, though MBT should precede landfilling in order to reduce the waste content of organic matter and thus reduce gas generation and emission at the landfill. MBT can include either a composting step or an AD step; in both cases, the output may be contaminated (e.g. heavy metals or organic toxic chemicals) and, thus, should not be used on agricultural land to replace fertilisers.
- When, for any reason, incineration and MBT are not available/viable, landfilling should include all measures to reduce emissions to the environment, e.g. leachate and gas collection and treatment, bottom and side liners, and top soil cover. However, in case the target set by the Landfill Directive on reduction of landfilling of biodegradable waste is not met, it becomes necessary to create additional capacity for one of the options higher up in the waste hierarchy to reduce long-term problems associated with landfills.

2.5 Conducting a new LCA for waste management: an overview

When LCA is applied to waste management, typically the assessment focuses on a comparison of different waste management options that do not cover the entire life cycle of the products which have become waste. For example, when evaluating different options for bio-waste management, usually the production stages of the food that has become bio-waste are not considered. However, if one of the evaluated waste management options includes that materials are given back into the life cycle of a product, a product life cycle perspective has to be taken into account, i.e. cradle to grave. For instance, when looking at municipal waste management including recycling, the benefits of saving virgin raw materials in the production stages of products have to be taken into account.

Conducting an LCA requires to follow this five-phase procedure: goal definition, scope definition, life cycle inventory, life cycle impact assessment and interpretation of results. In addition, reporting and critical review should also be undertaken. LCA is an iterative process. For example, one might need to go back and revise the initial definition of goal and scope based on the learning from the inventory analysis. For instance, it may be necessary to refine the system boundary to include a process that was initially disregarded.

A crucial task in the LCA scope definition is to identify the "functional unit", i.e. the service or function the investigated system delivers to the user(s). In municipal waste management, the functional unit can be, for instance, the collection and treatment of all bio-waste in a given region and year. All environmental burdens are then expressed relative to this functional unit. For comparing different waste management options or systems, it is crucial that they provide the same function. Otherwise, a fair comparison between systems is not possible.

More detailed, waste-specific guidance on how to conduct an LCA for waste management are given in the earlier mentioned document "Supporting Environmentally Sound Decisions for Waste Management—A technical guide to Life Cycle Thinking (LCT) and Life Cycle Assessment (LCA) for waste experts and LCA practitioners".

3 Conclusions and perspectives

Large quantities of bio-waste are produced yearly in many countries around the globe. Improper management of bio-waste has shown to have adverse environmental effects, especially in terms of greenhouse gas emissions. In Europe, more than 1/3 of the bio-waste generated is still

landfilled untreated; this will no longer be in line with the targets set by the LD (1999/31/EC) on reduction of landfilling of biodegradable waste.

The WFD (2008/98/EC) established the waste hierarchy, a legally binding order of environmental preference amongst different waste management options. When the waste hierarchy is applied to bio-waste, it reads as follow: prevention, anaerobic digestion, composting, incineration and landfilling as the least desirable option.

However, the waste hierarchy might not lead to the overall best environmental solution. Article 4 of the WFD, in fact, suggests that deviations from the hierarchy are acceptable when justified by LCT on the overall environmental impacts of the different options. Amongst the existing LCT-based tools applied to waste management, LCA is being more and more used to quantify potential environmental impacts. Quantification of environmental impacts enables fair comparisons amongst alternative waste management options, which in turn allows verifying the environmental correctness of the hierarchy on a case-by-case basis.

In order to provide a more informed and science-based support to policy-making, the EU JRC has developed guidelines that aim at providing LCT/LCA-based support to decision-making for bio-waste management. This provides practical guidance on how to recognise key technical and environmental parameters and, ultimately, identify the environmentally preferable management option for bio-waste. It was found that conducting a full LCA is not always necessary for providing robust environmental assessments. In fact, in application contexts such as day-to-day decision-making, robust LCT/LCA-based knowledge may exist that can help identify the preferable option.

The necessary efforts and resources that need to be invested in an LCA may seem to be high. However, these costs have to be put into the broader context of the investments necessary to build up and maintain sustainable waste management infrastructures.

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